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AEROBRAKING FOR CAPTURE INTO MARTIAN ORBIT

by

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ABSTRACT

The paper is a summary of several studies into problems associated with aerobraking a manned vehicle into a Martian capture orbit. The problems investigated are:

1) The establishment of entry flight path angle windows that allow aerocapture.

2) The determination of the sensitivity of the entry trajectory to initial flight path angle.

3) The determination of the effect on aerocapture of the assumed Martian atmosphere model.

4) The determination of the effect of random atmosphere disturbances on adaptive guidance systems that may be used for aerocapture.

As a result of investigating the above problem areas, entry windows were established for three different vehicle configurations. Sensitivities to changes in initial flight path angle were also obtained for these three configurations. One configuration was chosen to determine the effect of Martian atmospheric model changes and random variations of density within a specific atmospheric model. Of particular interest was the effect of random density variations on adaptive guidance techniques. The effect of entry velocity on the size of the entry window was also examined.

INTRODUCTION

Aerobraking has been identified as an enabling technology for manned Mars missions because of weight savings in propulsion fuel (ref.1). The accuracies required for Martian entry that guarantee aerocapture must be established.

Guidance techniques to accomplish aerocapture must also be determined. The guidance must be adaptable and robust enough to compensate for a wide range of atmospheric disturbances among which density variation has the greatest impact on guidance performance. In this paper only density variations will be considered.

For the types of vehicles envisioned for the manned Mars mission the guidance technique generally employed is bank angle lift modulation. Lift modulation is achieved by rotating the vehicle through various bank angles to change the magnitude of the lift component in the vertical plane of the entry trajectory. The vehicle will penetrate into the atmosphere to a given altitude and then the drag will slow the vehicle enough to ensure capture. After capture velocity is reached, the vehicle tends toward lift up attitude so that it can escape from the atmosphere of Mars and go into orbit. Lift modulation is used to adjust the level of penetration into the atmosphere and how quickly the vehicle exits the atmosphere so that operational constraints can be satisfied.

Since this is a preliminary study, a range of possible manned Mars vehicles was considered. Basically, all of the vehicles will accommodate a 6- to 8- person crew and be designed for missions of up to 2 years. Within this framework vehicles with a range of ballistic coefficients were studied to establish combinations of initial flight path angle and bank angle required for capture into Martian orbit. To establish these angles, entry flight path angle windows and the sensitivity to entry flight path angle for aeropass trajectory parameters were determined. Next,bank angle profiles required for aerocapture for different vehicles were investigated. Simulated guidance profiles using fixed bank angle sequences were used to determine the sensitivity to bank angle for various vehicles and for different Martian atmospheres.

Using the results of the studies with fixed bank commands two adaptive guidance techniques were developed. In this paper adaptive guidance is a procedure for continuously changing the bank commands to the vehicle control system. So that these guidance techniques could be tested in a realistic environment, a random Martian atmosphere was developed. By incorporating the random atmosphere into the program used to simulate Martian entries, the adaptive guidance techniques were tested under conditions of random density variation. Monte Carlo techniques were used to establish success boundaries for the various guidance techniques so that their adaptability to random density variations could be demonstrated.

This paper will discuss the entry windows for several potential manned Mars mission vehicles , the sensitivity to the entry flight path angle, the bank angle profiles required for Martian aerocapture and the "survivability" of adaptive guidance techniques in a randomly varying Martian atmosphere.

SYMBOLS

A	area, m^2
a	acceleration, m/sec^2
C_D	drag coefficient
C_L	lift coefficient

h_p	perigee altitude,km
Δh_p	change in perigee altitude, km
$h_{p,p}$	predicted perigee altitude, km
$h_{p,T}$	target perigee altitude, km
k	feedback gain
L/D	lift-to-drag ratio
M	mass, kg
S_c	current vehicle state
S_N	vehicle state from baseline trajectory
V_I	velocity, m/sec
ΔV_I	change in velocity, m/sec
ϕ	commanded bank angle, degrees
ϕ_N	bank angle from baseline trajectory, degrees
γ_I	initial flight path angle, degrees
$\Delta\gamma_I$	change in initial flight path angle, degrees

ABBREVIATIONS

ALTITO	altitude, m
BNKANG	bank angle, degrees
DENS	density, kg/m^3
ENERGY	energy per unit mass, m^2/sec^2
POST	program to optimize simulated trajectories
TIME	time, sec
VELI	velocity, m/sec
ASMG	acceleration, "g" units

APPROACH

The studies discussed in this paper were made using the Program to Optimize Simulated Trajectories (POST). This program can be used to determine initial parameters and control parameters throughout a trajectory to accomplish stated mission objectives. The simulations were started at 300,000 meters and at an entry angle selected by the user. Initially, a fixed number of bank angles were chosen to represent an entry guidance system. By varying the magnitudes of these bank angles the lift force is modulated to control the trajectory of the vehicle. Runs were considered successful if capture was achieved, the maximum acceleration was less than 5 "g"s, and the minimum altitude was greater than 30 kilometers.

Studies were run for the vehicles described in Table I which contains the characteristics required to calculate the ballistic coefficients of the three vehicles used in this study. A large number of bank angles was used to ensure capture. To establish the entry window the maximum and minimum flight path angles for which capture was possible were determined. The difference in these flight path angles was the entry window. During the runs the sensitivity of the trajectory to flight path angle and bank angle was calculated by POST.

Once the trends in bank angle magnitude for various vehicles and entry conditions were determined, then an attempt was madeto establish the minimum number of bank commands that were required for aerocapture. One of these "fixed" bank profile trajectories became the nominal for the adaptive guidance.

Various Martian atmosphere models obtained from David Pitts et al. at Johnson Space Center were used to determine the effects of varying Martian atmospheres. When the random Martian atmosphere was developed, these same data were used as the nominal for the perturbed atmosphere. The random atmosphere subroutine allowed different levels of density variation.

The two adaptive guidance techniques to be discussed in this paper are presented in reference 3. Adaptive guidance 1 is a trajectory following technique and adaptive guidance 2 is a predictor-corrector technique In summary, the adaptive techniques adjust the bank angle to change the orientation of the lift vector and control the entry trajectory. Adaptive guidance 1 follows a nominal trajectory that gives an acceptable entry. The guidance used in this study compared the actual and nominal energies at the current velocity. The form of the bank angle command equation was $\phi = \phi_N + k * (E_C - E_N)$. This technique tried to correct to a nominal energy when the trajectory was perturbed by density variations.

Adaptive guidance 2 predicted the perigee altitude based on current conditions and adjusted the bank angle to try to attain a desired perigee altitude. The form of the bank angle command was $\phi = \phi_N + k * (h_T - h_p)$. Once perigee was reached the vehicle was rolled to a specified bank angle until the Martian capture velocity was attained and then the vehicle was rolled to full lift up for escape from the atmosphere. The adaptive guidance techniques implemented were not optimal but were used to determine the effect of a random atmosphere on representative guidance systems.

A program for establishing requirements for and evaluating the performance of guidance techniques was developed by combining the guidance subroutines, the random Martian atmosphere program, and the basic POST software. The results and discussion section, which follows, will discuss applications of this program.

RESULTS AND DISCUSSION

The initial investigations to determine Martian aerocapture characteristics were conducted using a hypothetical manned vehicle with a $M/C_DA = 620.5$ and $L/D = 1$ (ref. 4). Since the sensitivity to bank angle was unknown, the initial entries were made using a simulated guidance that would allow 16 bank changes during the aeropass. Using this simulated guidance, the maximum and minimum entry flight path angles for which capture was possible were determined. Typical time histories of these aerobraking trajectories are shown as figures 1 and 2. As can be seen from examination of the bank angle time histories, about nine of the possible bank angle changes were required for the maximum flight path angle entry and six for the minimum flight path angle entry. This gave an indication of the amount of maneuvering an entry might require.

The POST program calculates the sensitivity of entry trajectory parameters to entry flight path angle. Typical sensitivities to entry flight path angle and the maximum and minimum flight path angles possible for two proposed manned vehicles are shown in figure 3. The sensitivity is generally larger for the maximum flight path angle entries since they fly higher in the atmosphere, have smaller lift components and are, therefore, less able to correct for disturbances.

The entry windows $\Delta\gamma_i$ (difference between the maximum and minimum entry angles) are shown as Table II for two potential manned Mars entry vehicles. Table II gives the maximum and minimum entry flight path angles and $\Delta\gamma_i$ for several L/D ratios determined by assuming a fixed drag coefficient and changing the lift coefficient. The entry flight path angles for which aerocapture was possible showed almost no change with ballistic coefficient; however, the change in entry flight path angle with L/D was significant. As the lift that was available to be modulated to control the vehicle was reduced,the size of the entry window decreased.

The sensitivities to entry flight path angle for several vehicles with different L/D values and ballistic coefficients are given as Table III taken from reference 5. This table was generated by taking an entry flight path near the center of the entry window and varying this angle by .001 degrees from the chosen entry angle. The results of the runs with the modified angle were compared with a run made using the original entry angle and the Δ parameter to $\Delta\gamma_i$ ratios were obtained. These sensitivities and window sizes can be used to establish navigation and guidance accuracy requirements.

Thus far, only aerobrake shapes with large nose radii have been discussed. However, for completeness a more streamlined vehicle with significantly less drag and a much larger ballistic coefficient was examined (Table I). The entry windows for this vehicle are given in Table IV. Since this vehicle penetrated deeper into the atmosphere the minimum entry flight path angle was constrained by altitude considerations and the entry windows were smaller for this vehicle.

Aerobraking entries were run with several other Martian atmospheric models. The aerobraking trajectories showed very little impact due to the change in atmospheric model. These results are shown in references 4 and 5 .

Results presented earlier indicated that the number of bank commands required for successful aerobraking could be greatly reduced. The vehicle referred to as blunt vehicle type 1 (Table I) was shown to require six or less bank commands when a L/D of .5 was assumed (figure 4). Since nominal entries will be flown near the center of the entry corridor to allow as much margin as possible before capture trajectory limits are encountered, runs were made with entry flight path angles near the middle of the entry windows. These show that less guidance activity was required for the nominal runs, but these runs are only for a deterministic atmosphere. Using a deterministic atmosphere and flying near the middle of the entry corridor, capture trajectories were generated that required only two commanded bankangles. One of these was chosen as the nominal trajectory of adaptive guidance 1.

So that the more realistic case of the effect of random disturbances on a guidance system could be tested, a random Martian atmosphere generator was implemented as a subroutine to POST. This combination enabled the adaptive guidance techniques to be tested in a realistic environment. When random density variations of up to 50 percent were allowed, both adaptive guidance routines gave acceptable capture trajectories. Typical entry trajectories with 50 percent random density variations as compared to a trajectory using a deterministic density profile are shown as figures 5 and 6. Adaptive guidance 2 also gave acceptable results for maximum density variations of up to 86 percent. This assessment, discussed in reference 5, was based on a limited number of runs.

Since adaptive guidance 2 seemed the most tolerant to large density variations, Monte Carlo runs were made to establish the success of the guidance for a large number of runs. One hundred runs were made at each of two density variation levels for adaptive guidance 2. The variations were from the deterministic density of figure 6 and the results are comparisons to various parameters from figure 6. When the first variation level wasused, the maximum density variation was such that 90 percent of the maximum densities fell within a plus/minus 60 percent band about the maximum deterministic density. In spite of large density variations, the final periods of the capture orbits fell within a plus/minus 20 percent band of the deterministic density orbital period 88 percent of the time. The acceleration was over 5"g"s only 6 percent of the time and at no time was the acceleration over 5.5 "g"s. All of the perigee altitudes were greater than 34 kilometers. All of the entries resulted in capture.

To see how far the maximum density could be varied and the guidance still be successful, an additional one hundred runs were made with the second level of maximum density variation. In this case 96 percent of the maximum densities fell inside a plus/minus 120 percent band about the deterministic maximum density. The final periods of the resulting orbits fell within plus/minus 20 percent of the deterministic density orbital period value 44 percent of the time and within plus/minus 30 percent 77 percent of the time.

In spite of the fact that all the perigee altitudes were greater than 34 kilometers because of the larger maximum densities, many of the maximum accelerations were large. The maximum acceleration was greater than 5 "g"s 40 percent of the time and greater than 5.5 "g"s 23 percent of the time. In all cases, capture was achieved.

Although 40 percent of the cases exceeded the 5 "g" limit imposed on the capture trajectory, the density variations in the order of 100 percent are probably extreme. The results using the 60 percent variations are probably more realistic. The fact that a very simple guidance performed well with large density variations implies that a more optimal guidance should be very successful.

All of the runs were made using an entry velocity of 6.7 kilometers/sec. This entry velocity is on the low end of possible entry velocities for manned Mars missions (ref. 1).Several additional runs were made using vehicle described as a blunt vehicle type 1 (Table I), and having a L/D of .5. Entry velocities of 7.5 kilometers/sec and 8.0 kilometers/sec were tested. The results are shown in Table V . The entry velocity had no effect on the trajectories that flew lowest in the atmosphere (minimum γ_i). However, the entry angles for which capture was possible for trajectories passing higher in the atmosphere (maximum γ_i) became much more negative as velocity increased. Because of the added energy the vehicle had to pass lower in the atmosphere to be captured, thereby, reducing the entry window.

CONCLUDING REMARKS

Potential manned Mars mission vehicles with large nose radii and L/D's of .5 were found to have entry flight path angle windows of over 1 degree. For these windows the sensitivity to change in initial flight path angle tended to be greater for trajectories that flew higher in the atmosphere. The size of the windows changed very little with ballistic coefficient, but were smaller as L/D decreased.

Vehicles with an L/D of .5 that flew near the middle of the entry corridor required very little guidance activity to obtain capture for the deterministic case. However, when flying near the top of the entry corridor or when random disturbances were encountered, more guidance response was required. To determine the extent of the guidance response required to adapt to density disturbances, a random Martian density generator and two adaptive techniques were developed.

The guidance techniques were tested at several levels of maximum random density variation for a limited number of runs. Both adaptive guidance techniques gave acceptable results for random variations of up to 50 percent. Adaptive guidance 2 had better performance at higher levels of random density variation, so it was tested for 100 cases using Monte Carlo techniques. For maximum density variations of up to 60 percent, 96 percent of the runs resulted in acceptable entries.

Increasing the entry velocity reduced the entry flight path angle window for which capture was possible.

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4. Lee, Mary C.; and Suit, William T.: Preliminary Investigation of Parameter Sensivities for Atmospheric Entry and Aerobraking at Mars, NASA TM 101607, September 1989.

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Table I. Vehicle Characteristics

Blunt Vehicles		
Vehicle Type 1	$M = 226{,}378$ kg $A = 182.415\ \mathrm{m}^2$	$M/C_DA = 919.3\ \mathrm{kg/m}^2$ $C_D = 1.35$
Vehicle Type 2	$M = 226{,}378$ kg $A = 182.415\ \mathrm{m}^2$	$M/C_DA = 620.5\ \mathrm{kg/m}^2$ $C_D = 2$
Streamlined Vehicle		
Vehicle Type 1	$M = 136{,}116.2$ kg $A = 79\ \mathrm{m}^2$	$M/C_DA = 2970.7\ \mathrm{kg/m}^2$ $C_D = 0.58845$

Table II. Entry Angle Windows for Blunt Vehicles

L/D	M/C_DA ($\mathrm{kg/m}^2$)	C_D	Max γ_i	Min γ_i	$\Delta\gamma_i$
0.3	620.5	2	−18.3193°	−19.1109°	0.7916°
0.3	919.3	1.35	−18.4461°	−19.2344°	0.7883°
0.5	620.5	2	−18.2415°	−19.5880°	1.3465°
0.5	919.3	1.35	−18.3289°	−19.7263°	1.3974°
0.75	919.3	1.35	−18.2432°	−20.0423°	1.7991°
1.0	620.5	2	−18.0646°	−19.6747°	1.6101°
1.0	919.3	1.35	−18.3492°	−20.2000°	1.8508°

Table III. Sensitivity of Velocity, Altitude, and Acceleration to γ_i at Perigee for Two Potential Manned Mars Vehicles.

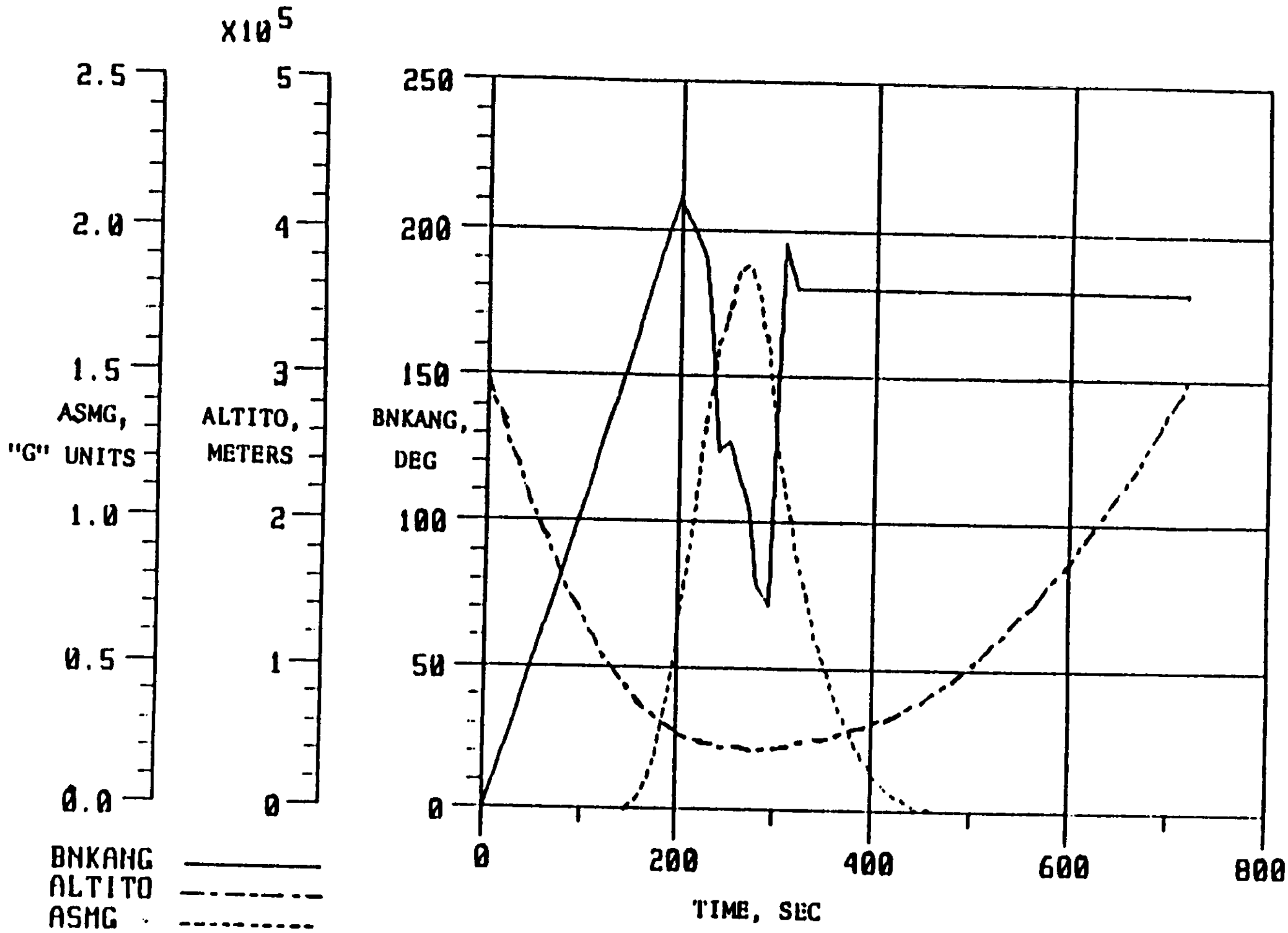
L/D	M/C_DA (kg/m²)	$\Delta\gamma_i$ (deg)	$\Delta V/\Delta\gamma_i$ (m/s/deg)	$\frac{\Delta h}{\Delta\gamma_i}$ (m/deg)	$\frac{\Delta a}{\Delta\gamma_i}$ (m/s²/deg)
0.3	919.3	+0.001	2.0×10^3	2.44×10^4	45.5
0.3	919.3	−0.001	2.0×10^3	2.38×10^4	44.6
0.5	919.3	+0.001	1.5×10^3	1.30×10^4	31.0
0.5	919.3	−0.001	1.5×10^3	1.20×10^4	29.5
0.75	919.3	+0.001	1.1×10^3	9.80×10^3	32.2
0.75	919.3	−0.001	1.1×10^3	9.80×10^3	31.7
1.0	919.3	+0.001	1.2×10^3	1.26×10^4	36.0
1.0	919.3	−0.001	1.2×10^3	1.26×10^4	36.0
0.5	2970.7	+0.001	2.3×10^3	2.84×10^4	43.3
0.5	2970.7	−0.001	2.3×10^3	2.86×10^4	86.5
0.75	2970.7	+0.001	3.8×10^3	7.33×10^4	48.8
0.75	2970.7	−0.001	3.8×10^3	7.63×10^4	48.8
1.0	2970.7	+0.001	3.1×10^3	6.09×10^4	52.8
1.0	2970.7	−0.001	3.1×10^3	1.23×10^5	53.0

Table IV. Entry Angle Windows for Streamlined Vehicle

L/D	h_p(km)	a_{max}(m/sec²)	γ_i(deg)	Comments	$\Delta\gamma_i$(deg)
.5	33.0	12.5	-18.637	Lift down	--
.5	30.0	18.3	-20.508	32 km limit	.663
.75	35.6	10.8	-18.513	Lift down	--
.75	32.1	17.0	-19.197	32 km limit	.684
1.0	37.9	10.0	-18.424	Lift down	--
1.0	32.1	19.6	-19.314	32 km limit	.890

Table V. Entry Angle Windows for Several Entry Velocities

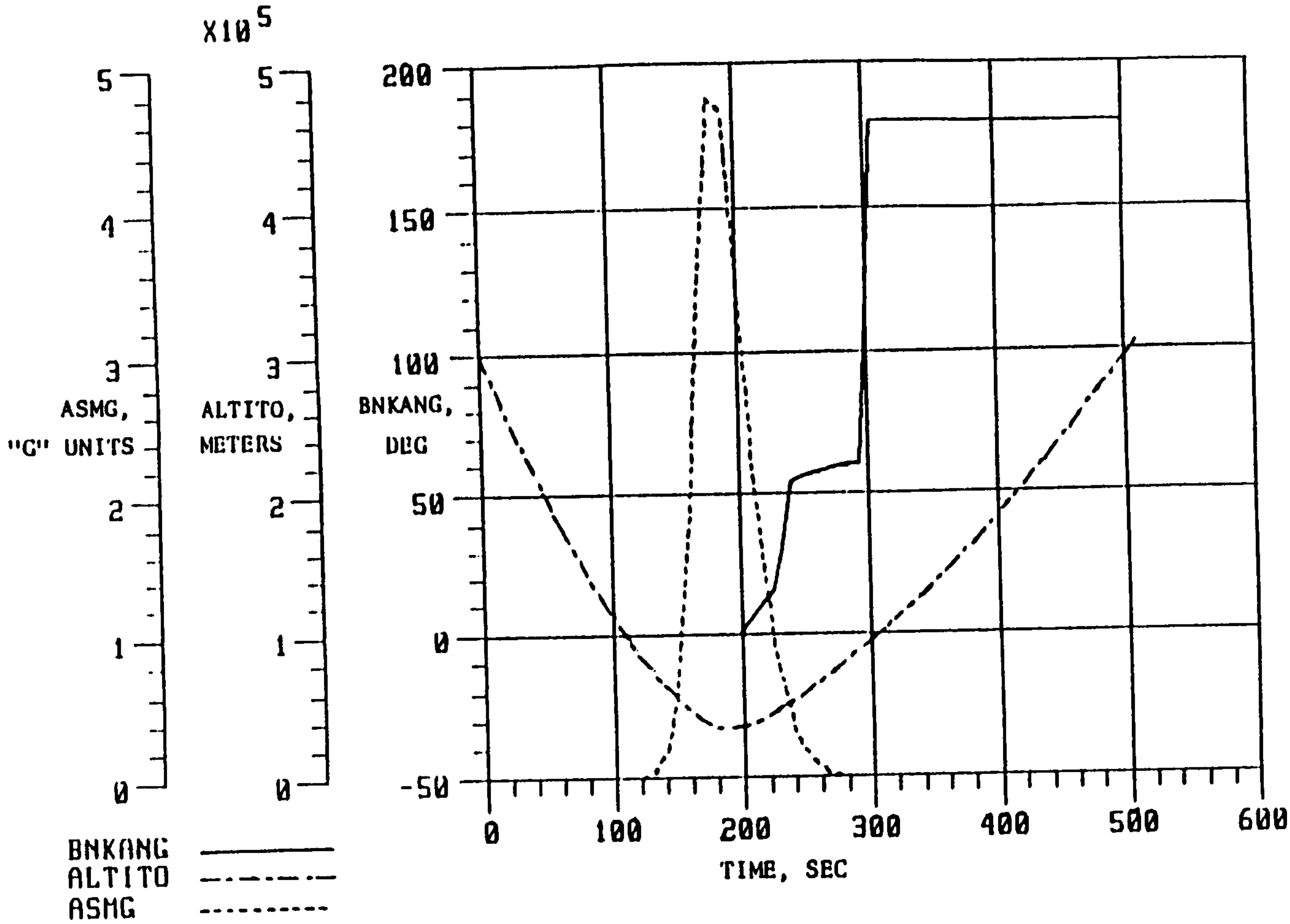
V_I	Max γ_i	Min γ_i	$\Delta\gamma_i$
6.7 km/sec	-18.3 deg	-19.8 deg	1.5 deg
7.5 km/sec	-18.9 deg	-19.8 deg	0.9 deg
8.0 km/sec	-19.2 deg	-19.8 deg	0.6 deg



Vehicle Type 2

$M/C_DA = 620.5$ $L/D = .5$

Figure 1. Time Histories of Bank Angle, Altitude, and Acceleration for a Maximum Flight Path Angle Martian Entry.

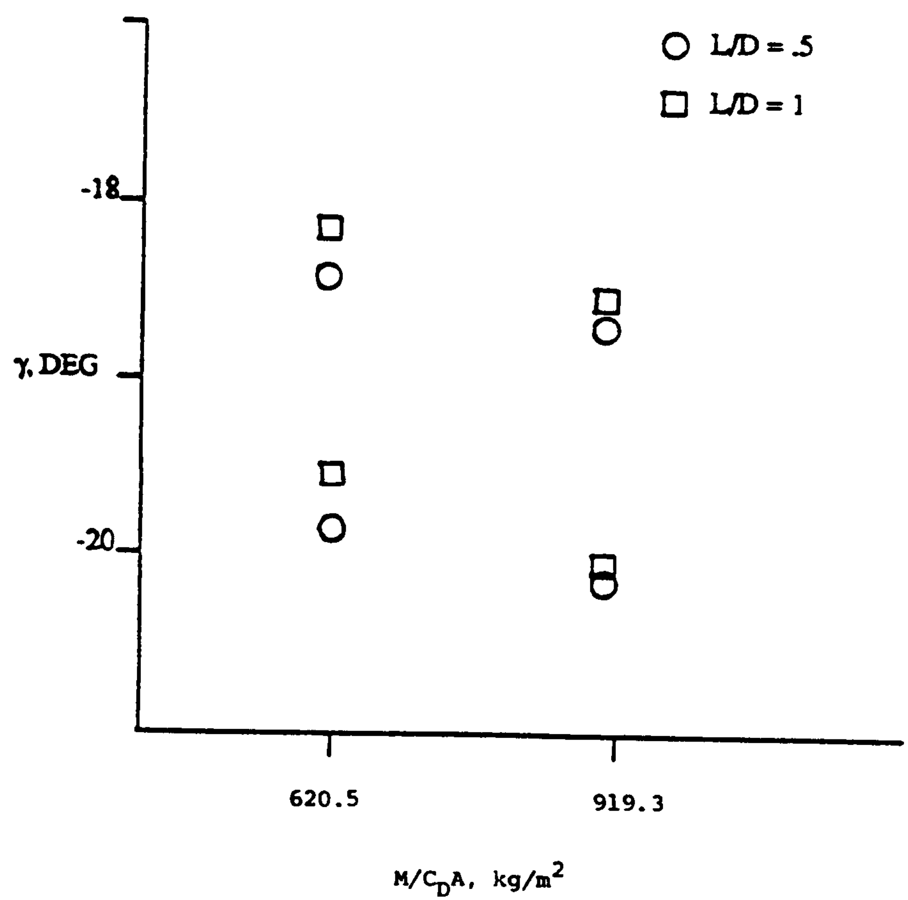


Vehicle Type 2

M/C_DA = 620.5   L/D = .5

Figure 2. Time Histories of Bank Angle, Altitude, and Acceleration for a Minimum Flight Path Angle Martian Entry.

MAXIMUM AND MINIMUM
ENTRY FLIGHT PATH ANGLES



TYPICAL SENSITIVITES

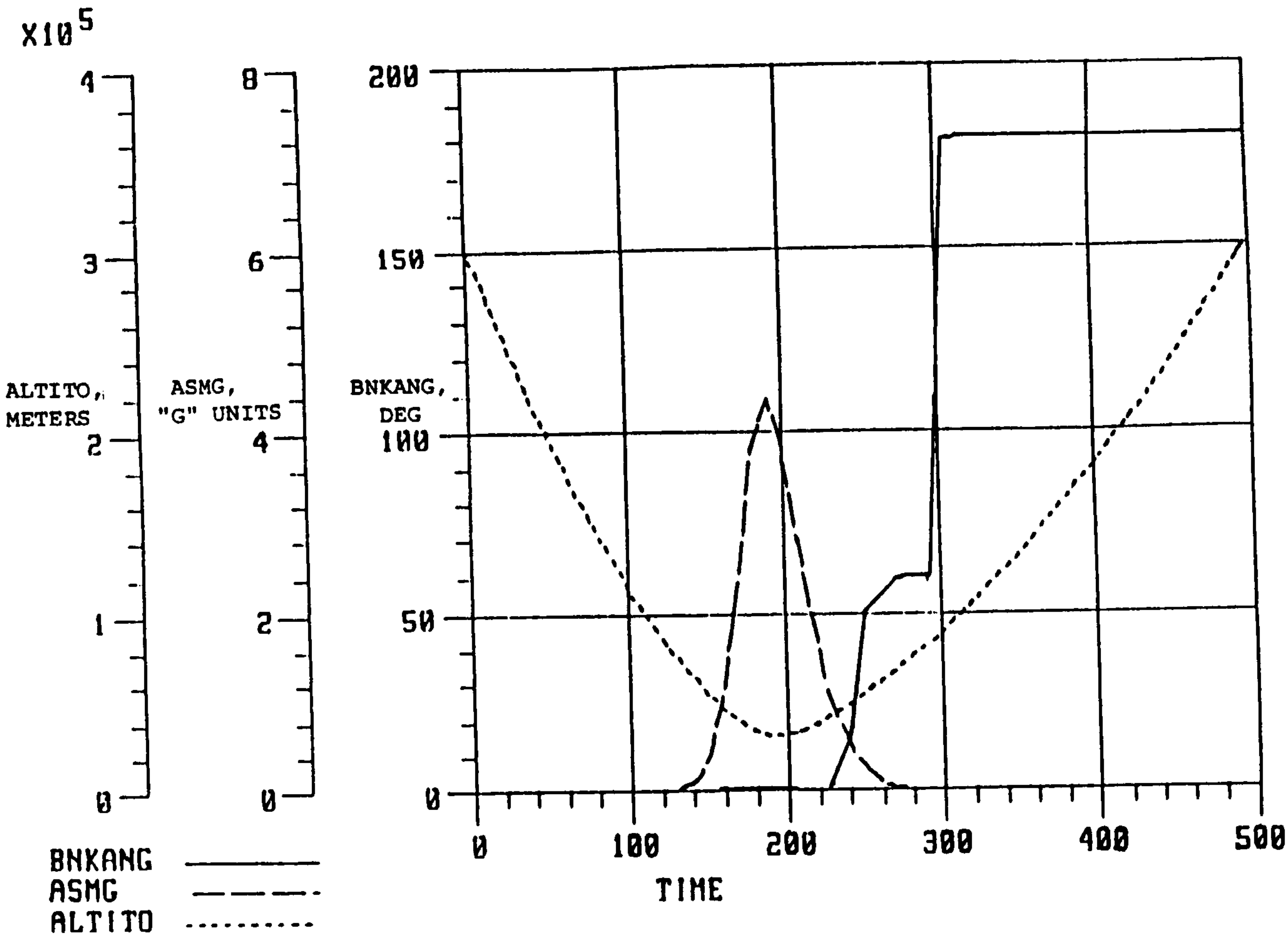
MAXIMUM FLIGHT PATH ANGLES

	L/D = 1	L/D = .5
$\left\lvert \frac{\Delta V}{\Delta \gamma_I} \right\rvert$	1.37E4	1.0E4

MINIMUM FLIGHT PATH ANGLE

	L/D = 1	L/D = .5
$\left\lvert \frac{\Delta V}{\Delta \gamma_I} \right\rvert$	3.85E3	.93E3

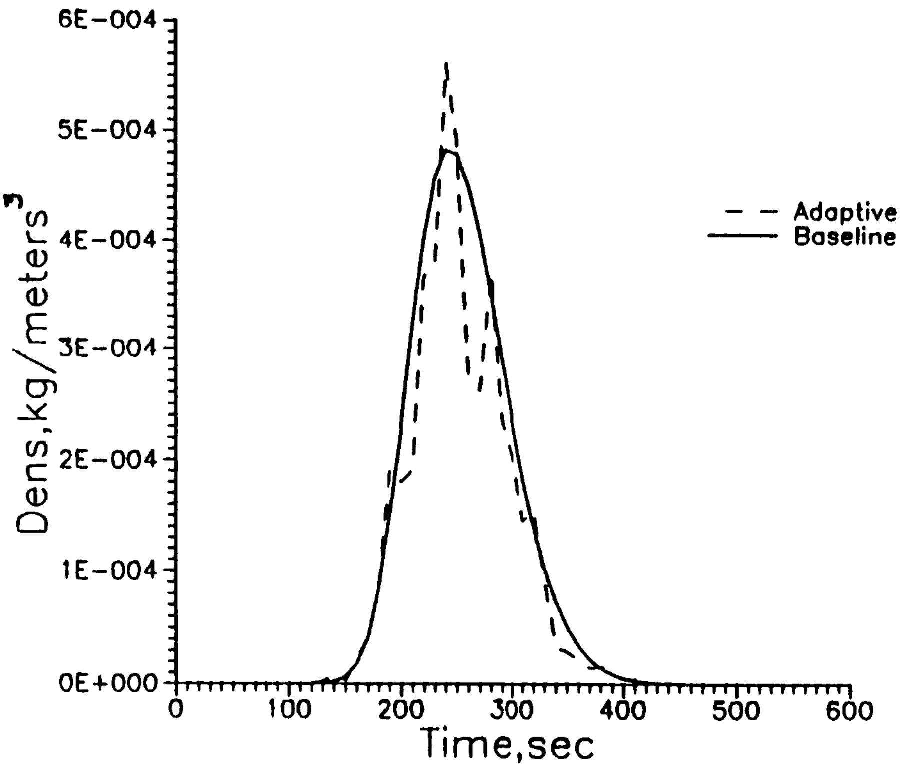
Figure 3. Flight Path Angle Windows and Typical Sensitivities for Two Proposed Mars Entry Vehicles.

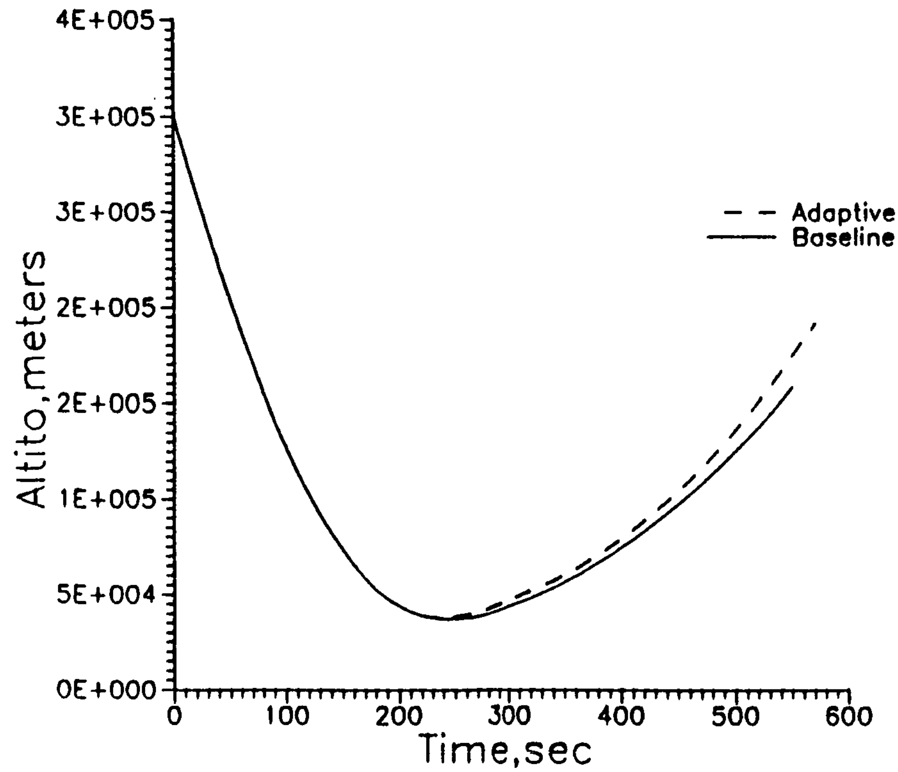


Vehicle Type 1

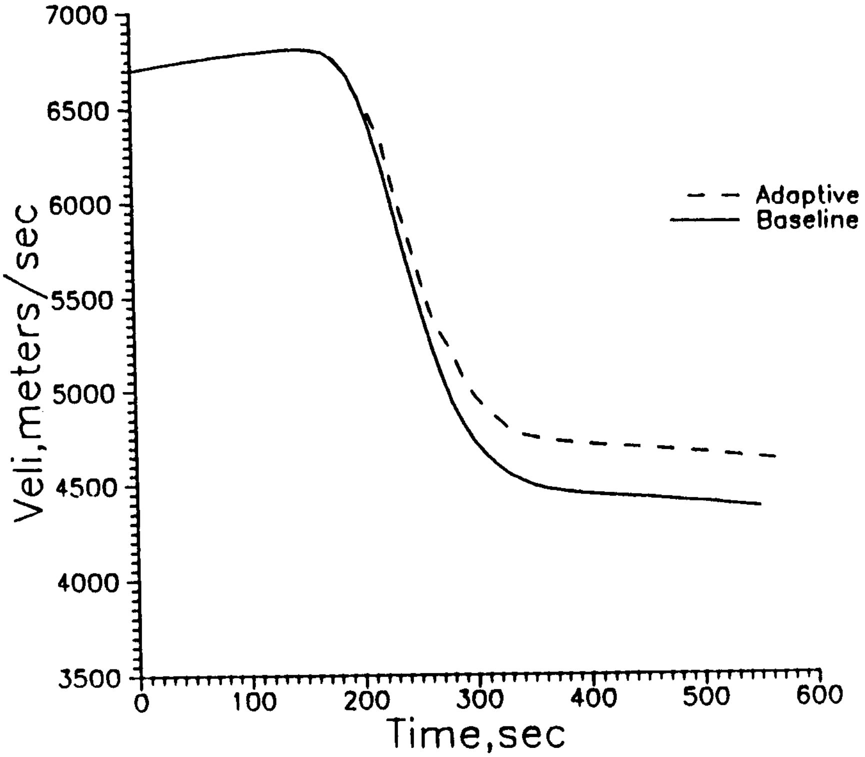
$M/C_DA = 919.3$ $L/D = .5$

Figure 4. Typical Time Histories of Bank Angle, Acceleration, and Altitude for a Martian Entry with Reduced Bank Commands.





igure 5. State and Atmosphere Time Histories for a Martian Aerocapture using Adaptive Guidance 1, with a Reduced Gain of $1x10^{-4}$, Flying Through a Random Atmosphere with Maximum Density Variations of 50 percent and for the Baseline Trajectory.



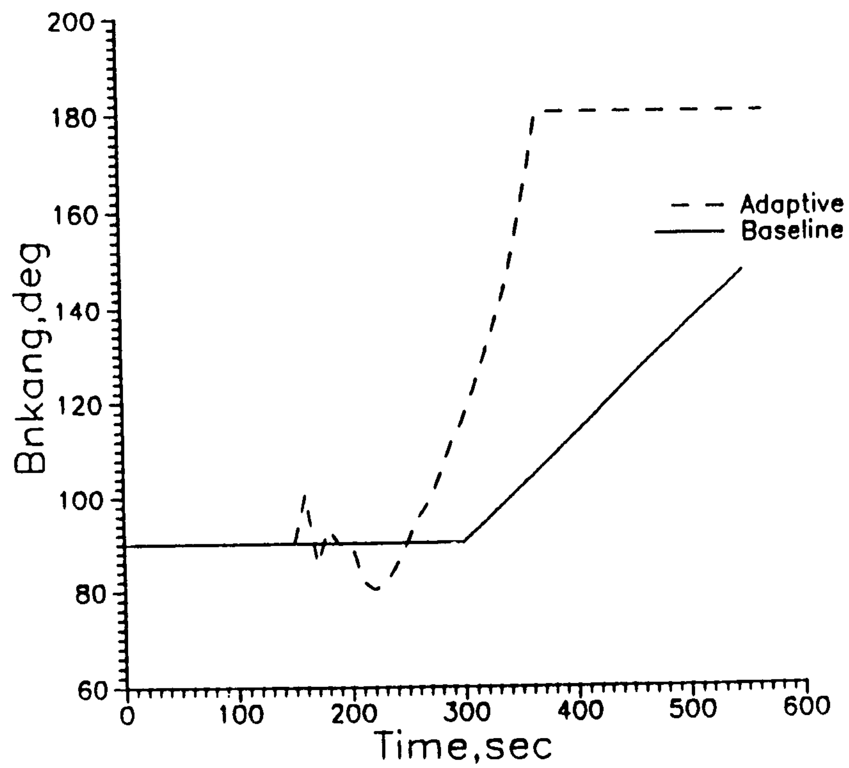


Figure 5. Continued.

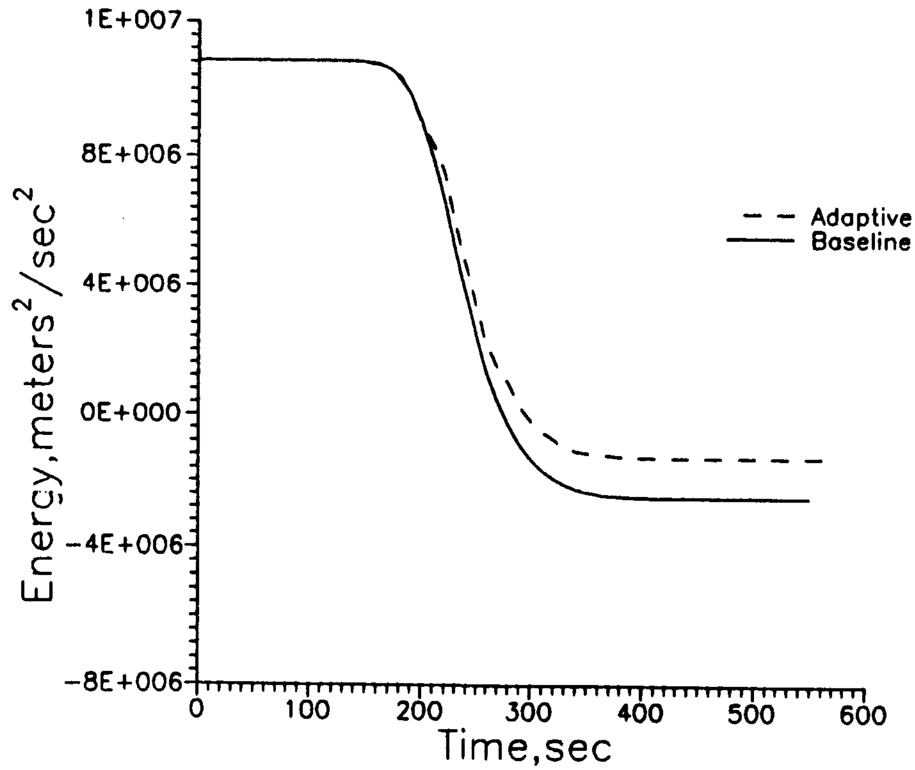


Figure 5. Concluded.

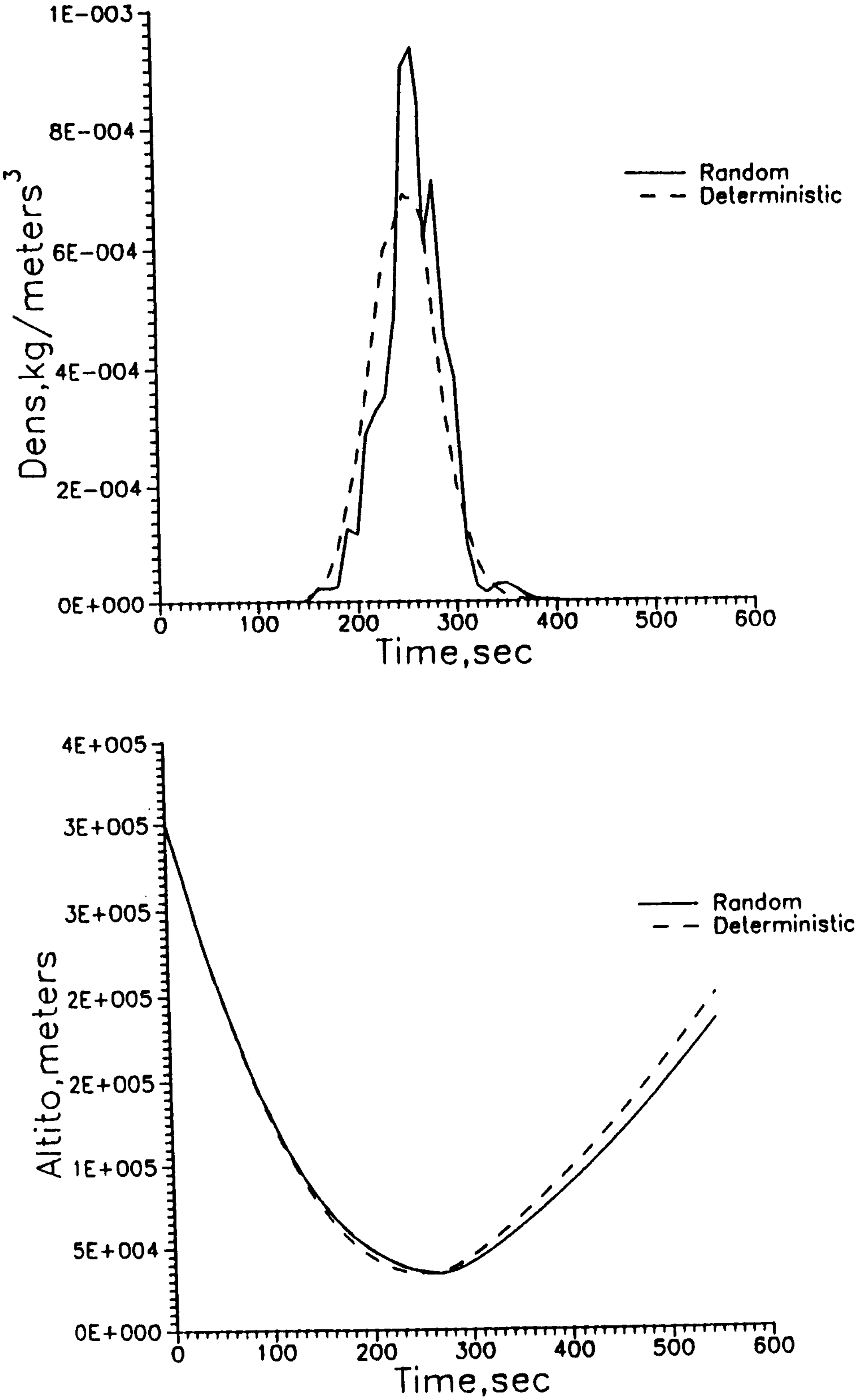


Figure 6. State and Atmosphere Time Histories for a Martian Aerocapture using Adaptive Guidance 2, Flying through a Random Atmosphere with Maximum Density Variations of 50 percent and for a Deterministic Atmosphere.

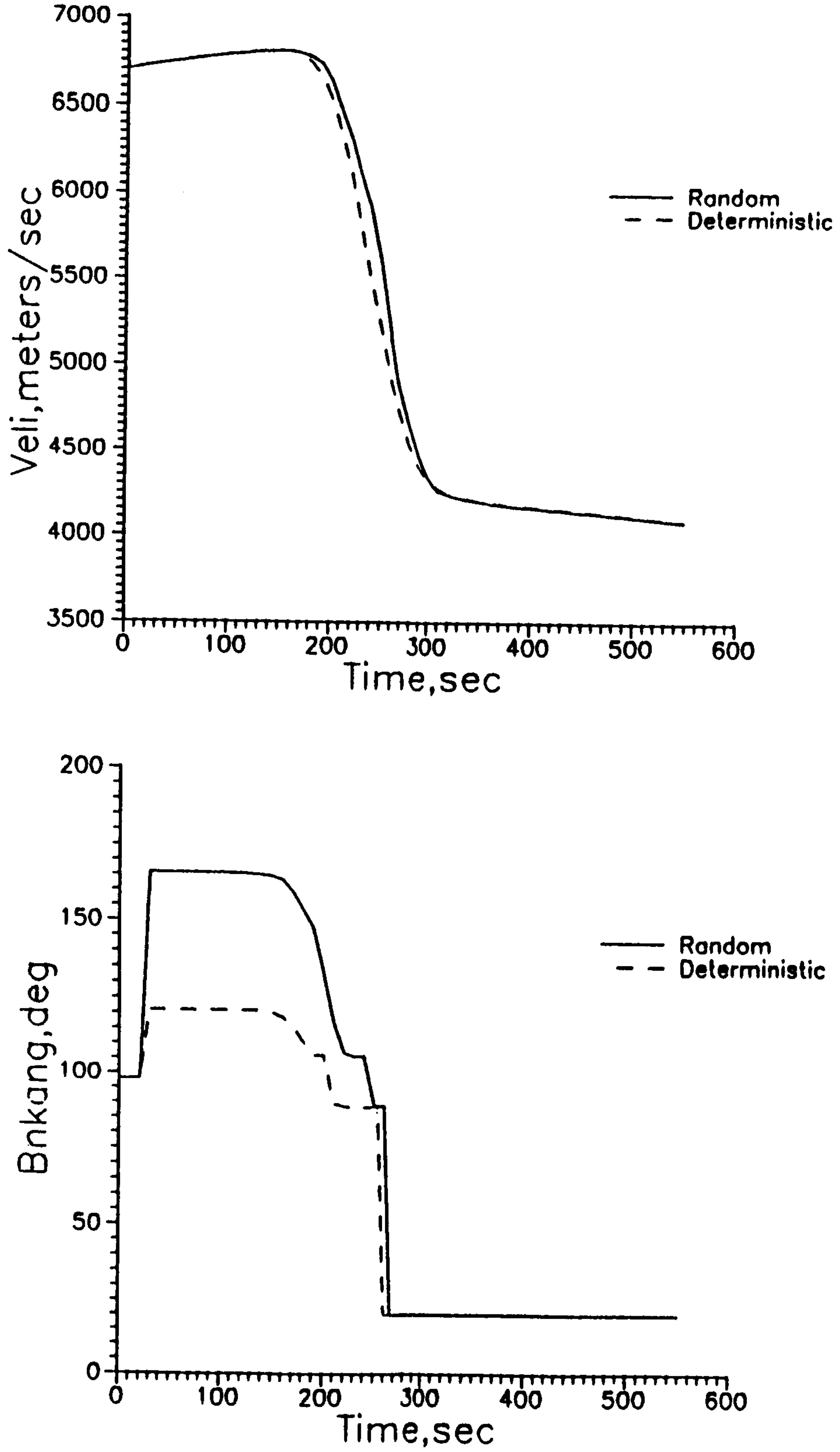


Figure 6. Continued.

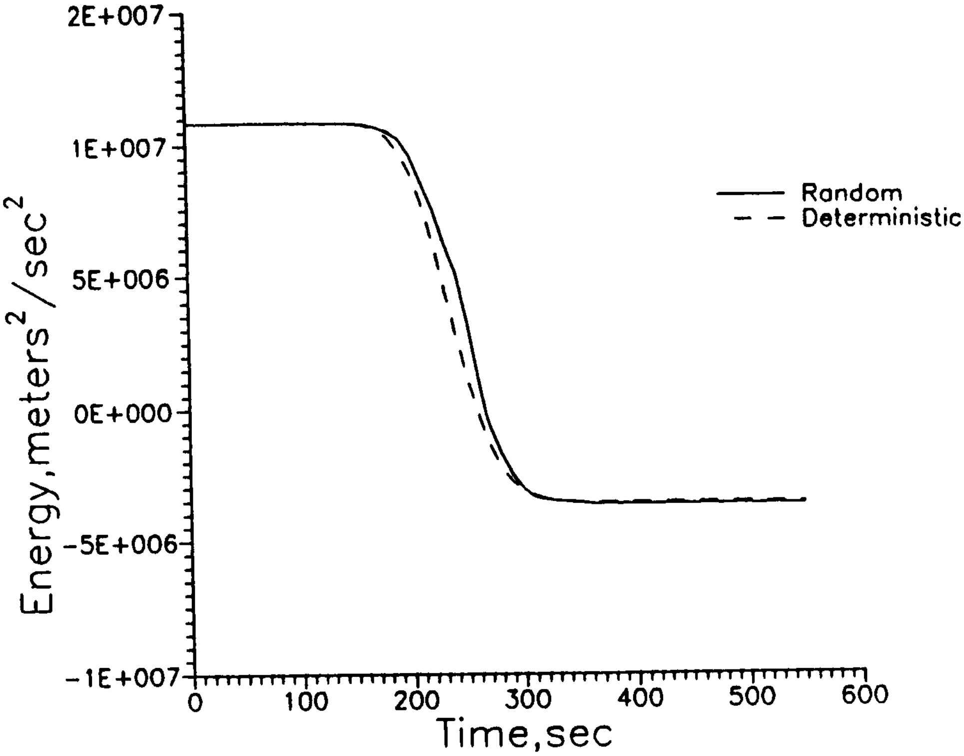


Figure 6. Concluded.